



SPECIAL REPORT

# REVOLUTION IN COSMOLOGY

**A**t a conference last May entitled "The Missing Energy in the Universe," cosmologists took a vote. Did they believe recent observations of distant exploding stars, which implied—in defiance of all expectations—that the universe is growing at an ever faster rate? Although astronomers have known since the 1920s that the universe is enlarging in size, pushing galaxies ever farther apart, they have always assumed that this expansion is mellowing out as gravity exerts its force of restraint. If in fact the growth is accelerating, the universe must be filled with some unknown form of matter or energy whose gravity repels rather than attracts. Hitherto unseen energy is, well, a repulsive thought for physicists. And yet of the 60 researchers present for the vote, 40 said they accepted the new findings.

Astronomers had suspected for more than a decade that all was not well in the halls of modern cosmology. When observers totted up the ordinary matter in the universe, it fell short of the amount needed to slow the cosmic expansion as predicted by the theory of inflation, an elegant explanation of the earliest stages of the big bang. Until now, the evidence against the theory has never been strong enough to overcome its advantages. But today even the theorists accept that something is amiss. At the very least, the expansion is not decelerating as rapidly as once thought. Either scientists must reconcile themselves to kooky energy, or they must modify or abandon inflation.

In this issue, *SCIENTIFIC AMERICAN* presents three sides of the story. First, three observers relate how and why their work on supernovae has caused such commotion. Then a theorist explains why these results attest to an ethereal energy that threads empty space. Finally, a pair of cosmologists offer another interpretation that extends the theory of inflation to times "before" the big bang.

—The Editors

# Surveying Space-time with

*Exploding stars seen across immense distances show that the cosmic expansion may be accelerating—a sign that the universe may be driven apart by an exotic new form of energy*

by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff

A long time ago (some five billion years), in a galaxy far, far away (about 2,000 megaparsecs), a long-dead star exploded with a flash brighter than a billion suns. Its light spread out across space, fading and stretching with the expanding cosmos, before some of it finally reached the earth. Within 10 minutes during one dark night in 1997, a few hundred photons from this supernova landed on the mirror of a telescope in Chile. A computer at the observatory then created a digital image that showed the arrival of this tiny blip of light. Though not very impressive to look at, for us this faint spot was a thrilling sight—a new beacon for surveying space and time.

We and our colleagues around the world have tracked the arrival of light from several dozen such supernovae and used these observations to map the overall shape of the universe and to chronicle its expansion. What we and another team of astronomers have recently discerned challenges decades of conventional wisdom: it seems the universe is bigger and emptier than suspected. Moreover, its ongoing expansion is not slowing down as much as many cosmologists had anticipated; in fact, it may be speeding up.

## Star Warps

The history of cosmic expansion has been of keen interest for most of this century, because it reflects on both the geometry of the universe and the nature of its constituents—matter, light and possibly other, more subtle forms of energy. Albert Einstein's general theory of relativity knits together these fundamental properties of the universe and describes how they affect the motion of matter and the propagation of light, thereby offering predictions for concrete things that astronomers can actually measure.

Before the publication of Einstein's theory in 1916 and the first observations of cosmic expansion during the following decade, most scientists

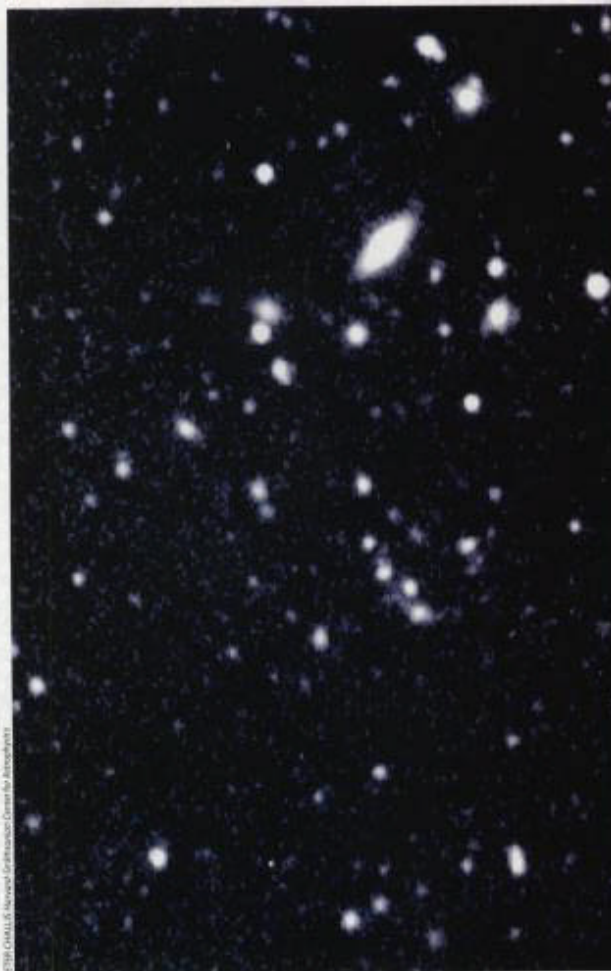


PHOTO COURTESY OF THE Hubble Space Telescope Center for Astronomers



# Supernovae



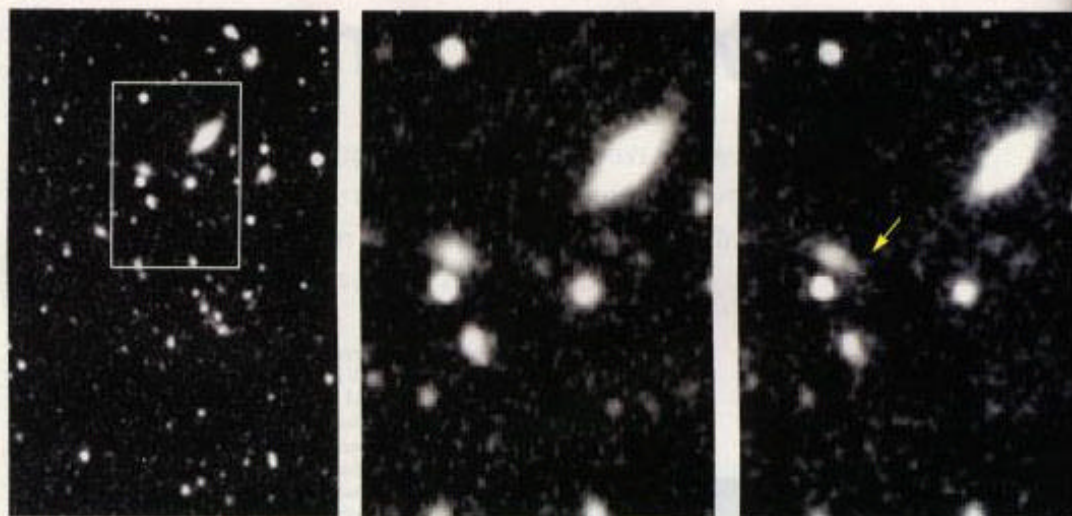
*Surveying Space-time with Supernovae*

thought the universe stayed the same size. Indeed, Einstein himself distrusted his equations when he realized they implied a dynamic universe. But new measurements of galactic motions by Edwin P. Hubble and others left no doubt: faint, distant galaxies were flying away from the earth faster than bright, nearby ones, matching the predictions of general relativity for a universe that grows and carries galaxies farther apart. These researchers determined the outward velocities of galaxies from the shift of visible spectral lines to longer wavelengths (so-called redshifts). Though often ascribed to the Doppler effect—the phenomenon responsible for changing the pitch of a passing train whistle or car horn—the cosmological redshift is more correctly thought of as a result of the ongoing expansion of the universe, which stretches the wavelength of light passing between galaxies. Emissions from more distant objects, having traveled for a greater time, become more redshifted than radiation from nearer sources.

The technology of Hubble's day limited the initial probing of cosmic expansion to galaxies that were comparatively close. In the time it took light from these nearby galaxies to reach the earth, the universe had expanded by only a small fraction of its overall size. For such modest changes, redshift is directly proportional to distance; the fixed ratio of the two is called Hubble's constant and denotes the current rate of cosmic expansion. But astronomers have long expected that galaxies farther away would depart from this simple relation between redshift and distance, either because the pace of expansion has changed over time or because the intervening space is warped. Measuring this effect thus constitutes an important goal for cosmologists—but it is a difficult one, for it requires the means to determine the distances to galaxies situated tremendously far away.

**WHERE'S THE SUPERNOVA?** This pair of images, made by the authors' team using the four-meter-diameter Blanco Telescope at Cerro Tololo Inter-American Observatory in Chile, provided first evidence of one supernova. In the image at the right, obtained three weeks after the one at the left, the supernova visibly (but subtly) alters the appearance of one of the galaxies. Can you find it? Some differences are caused by varying atmospheric conditions. To check your identification, consult the key on the next page.





DISTANT SUPERNOVA, with a redshift of  $z = 0.66$ , appears by the arrow. The explosion of this star affects just a few picture elements in the image taken after the event.

Hubble and other pioneers estimated distances to various galaxies by assuming that they all had the same intrinsic brightness. According to their logic, ones that appeared bright were comparatively close and the ones that appeared dim were far away. But this methodology works only crudely, because galaxies differ in their properties. And it fails entirely for distant sources whose light takes so long to reach the earth that it reveals the faraway galaxies as they were billions of years ago (that is, in their youth), because their intrinsic brightness could have been quite different from that of more mature galaxies seen closer to home. It is difficult to disentangle these evolutionary changes from the effects of the expansion, so astronomers have long sought other "standard candles" whose intrinsic brightness is better known.

To be visible billions of light-years away, these beacons must be very bright. During the early 1970s, some cosmic surveyors tried using quasars, which are immensely energetic sources (probably powered by black holes swallowing stars and gas). But the quasars they studied proved even more diverse than galaxies and thus were of little use.

About the same time, other astronomers began exploring the idea of using supernovae—exploding stars—as standard candles for cosmological studies. That approach was controversial because supernovae, too, show wide variation in their properties. But in the past decade research by members of our team has enabled scientists to determine the intrinsic brightness of one kind of supernova—type Ia—quite precisely.

#### Death Star

What is a type Ia supernova? Essentially, it is the blast that occurs when a dead star becomes a natural thermonuclear bomb. Spectacular as this final transformation is, the progenitor begins its life as an ordinary star, a stable ball of gas whose outer layers are held up by heat from steady nuclear reactions in its core, which convert hydrogen to helium, carbon, oxygen, neon and other elements. When the star dies, the nuclear ashes coalesce into a glowing ember, compressed by gravity to the size of the earth and a million times the density of ordinary matter.

Most such white dwarf stars simply cool and fade away, dying with a whimper. But if one is orbiting near another star, it can slurp up material from its companion and become denser and denser until a runaway thermonuclear firestorm ignites. The nuclear cataclysm blows the dwarf star completely apart, spewing out material at about 10,000 kilometers per second. The glow of this expanding fireball takes about three weeks to reach its maximum brightness and then declines over a period of months.

These supernovae vary slightly in their brilliance, but there is a pattern: bigger, brighter explosions last somewhat longer than fainter ones. So by monitoring how long they last, astronomers can correct for the differences and deduce their inherent brightness to within 12 percent. Over the past decade studies of nearby type Ia supernovae with modern detectors have made these flashes the best calibrated standard candles known to astronomers.

One of these candles lights up somewhere in a typical galaxy about once every 300 years. Although such stellar explosions in our own Milky Way are rare celestial events, if you monitor a few thousand other galaxies, you can expect that about one type Ia supernova will appear every month. Indeed, there are so many galaxies in the universe that, somewhere in the sky, supernovae bright enough to study erupt every few seconds. All astronomers have to do is find them and study them carefully. For the past few years, that effort has occupied both our research group, dubbed the "High-Z Team" (for the letter that astronomers use to denote redshift), a loose affiliation organized in 1995 by Brian P. Schmidt of Mount Stromlo and Siding Spring Observatories in Australia, and a competing collaboration called the Supernova Cosmology Project, which began in 1988 and is led by Saul Perlmutter of Lawrence Berkeley National Laboratory.

Although the two teams have independent programs, they are exploiting the same fundamental advance: the deployment of large electronic light detectors on giant telescopes, a combination that produces digital images of faint objects over sizable swaths of the sky. A prime example of this new technology (one



that has served both teams) is the Big Throughput Camera, which was developed by Gary M. Bernstein of the University of Michigan and J. Anthony Tyson of Lucent Technologies. When this camera is placed at the focus of the four-meter Blanco Telescope at Cerro Tololo Inter-American Observatory in Chile, a single exposure covers an area about as big as the full moon and creates a picture of about 5,000 galaxies in 10 minutes.

Finding distant supernovae is just a matter of taking images of the same part of the sky a few weeks apart and searching for changes that might be exploding stars. Because the digital light detectors can count the number of photons in each picture element precisely, we simply subtract the first image from the second and look for significant differences from zero. Because we are checking thousands of galaxies in each image pair, we can be confident that the search of multiple pairs will find many supernovae—as long as the weather is good. Fortunately, the location of the observatory, in the foothills of the Andes on the southern fringe of Chile's Atacama Desert (one of the driest places in the world), usually provides clear skies. Betting that we will make some good discoveries, we schedule observing time in advance on a battery of other telescopes around the world so that follow-up measurements can start before the supernovae fade away.

In practice, the search for exploding stars in the heavens whips up its own burst of activity on the ground, because we must acquire and compare hundreds of large, digital images at a breakneck pace. We commandeer computers scattered throughout the Cerro Tololo observatory for the tasks of aligning the images, correcting for differences in atmospheric transparency and image size, and subtracting the two scans. If all goes well, most of the galaxies disappear, leaving just a little visual "noise" in the difference of the two images. Larger

signals indicate some new or changing object, such as variable stars, quasars, asteroids—and in a few cases, supernovae.

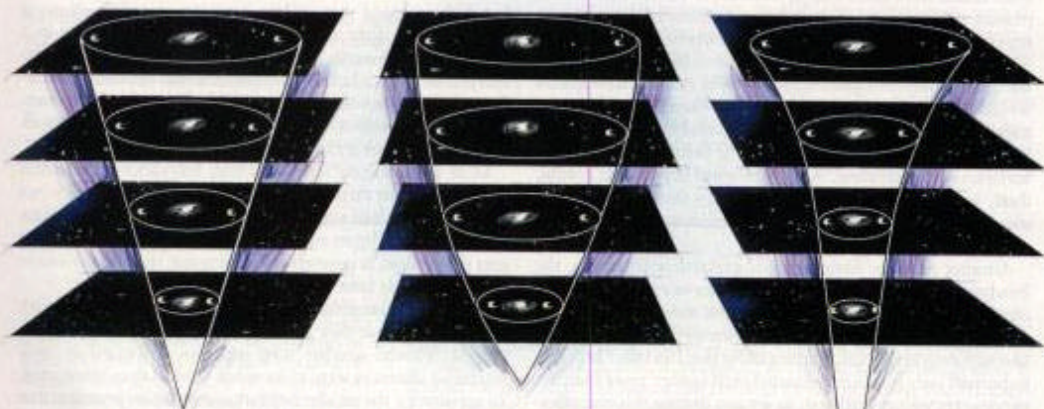
Our software records the position of new objects and attempts to identify which are truly supernovae. But the automated tests are imperfect, and we must scrutinize the images by eye to decide whether a putative supernova is real. Because we must immediately pursue our discoveries with other telescopes, the analysis must be done quickly. During these exhausting times, the observatory becomes a sweatshop of astronomers and visiting students, who work around the clock for days at a stretch, sustained by enthusiasm and Chilean pizza.

We next target the best supernova candidates with the largest optical instruments in the world, the recently constructed Keck telescopes in Hawaii. These critical observations establish whether or not the objects discovered are in fact type Ia supernovae, gauge their intrinsic brightness more exactly and determine their redshifts.

#### On the Dark Side

Others in our group, working with telescopes in Australia, Chile and the U.S., also follow these supernovae to track how their brilliance peaks and then slowly fades. The observing campaign for a single supernova spans months, and the final analysis often has to wait a year or more, when the light of the exploded star has all but disappeared, so we can obtain a good image of its host galaxy. We use this final view to subtract the constant glow of the galaxy from the images of the supernova. Our best measurements come from the Hubble Space Telescope, which captures such fine details that the exploding star stands out distinctly from its host galaxy.

The two teams have now studied a total of a few score high-

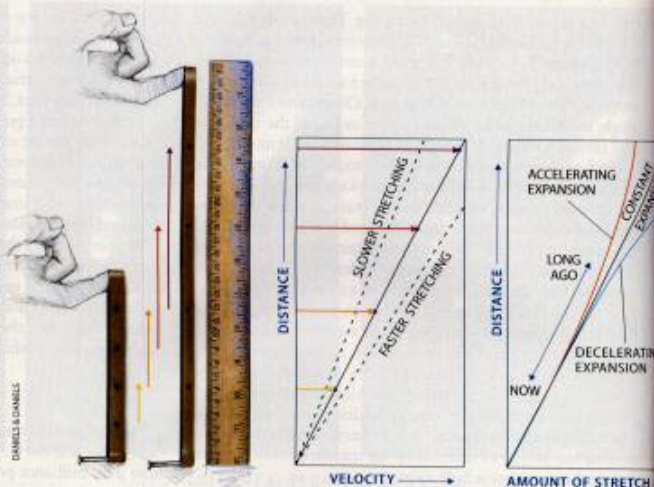


COSMIC EXPANSION could, in theory, follow one of three simple patterns: it may be constant (*left*), decelerating (*center*) or accelerating (*right*). In each case, a given portion of the universe grows in size as time passes (*from bottom to top*). But the age of the universe—the time elapsed since the beginning of the expansion—is greater for an accelerating universe and less for a decelerating universe, compared with the constant expansion case.

CAROLLO & GONZALEZ



**RUBBER BAND EXPERIMENT** shows the linear relation between recession velocity and distance. Here two snapshots are shown of a rubber band pulled upward at a certain rate. The velocity of different points marked on the band is given by the length of the colored arrows. For example, the point closest to the origin moves the least during the interval between snapshots, so its velocity is the smallest (yellow arrow). In contrast, the farthest point moves the most, so its velocity is the highest (violet arrow). The slope of the resulting line is the rate of expansion (left graph). If the rate changes over time, the slope, too, will change (right graph). Earlier times plot toward the upper right, because light from more distant objects takes longer to reach the earth, the origin of the plot. If the rate was slower in the past—indicating that the expansion has been accelerating—the line will curve upward (red line). If the rate was faster—as in a decelerating expansion—it will curve downward (blue line).



redshift supernovae, ones that erupted between four and seven billion years ago, when the universe was between one half and two thirds of its present age. Both groups were hit with a major surprise: the supernovae are fainter than expected. The difference is slight, the distant supernovae being, on average, only 2.5 percent dimmer than forecast. But this result is enough to call long-standing cosmological theories into question.

Before drawing any sweeping conclusions, astronomers on both teams have been asking themselves whether there is a prosaic explanation for the relative dimness of these distant supernovae. One culprit could be murkiness caused by cosmic dust, which might screen out some of the light. We think we can discount this possibility, however, because dust grains would tend to filter out blue light more than red, causing the supernovae to appear redder than they really are (in the same way that atmospheric dust colors the setting sun). We observe no such alteration. Also, we would expect that cosmic dust, unless it is spread very smoothly throughout space, would introduce a large amount of variation in the measurements, which we do not see either.

Another possible disturbance is gravitational lensing, the bending of light rays as they skirt galaxies en route. Such lensing occasionally causes brightening, but most often it causes demagnification and thus can contribute to the dimness of distant supernovae. Yet calculations show that this effect becomes important only for sources located even farther away than the supernovae we are studying, so we can dismiss this complication as well.

Finally, we worried that the distant supernovae are somehow different from the nearby ones, perhaps forming from younger stars that contain fewer heavy elements than is typical in more mature galaxies. Although we cannot rule out this possibility, our analysis already tries to take such differences into account. These adjustments appear to work well when we apply them to nearby galaxies, which range widely in age, makeup and the kinds of supernovae seen.

Because none of these mundane effects fits the new observa-

tions, we and many other scientists are now led to think that the unexpected faintness of distant supernovae is indeed caused by the structure of the cosmos. Two different properties of space and of time might be contributing.

First, space might have negative curvature. Such warping is easier to comprehend with a two-dimensional analogy. Creatures living in a perfectly flat, two-dimensional world (like the characters in Edwin A. Abbott's classic novel *Flatland*) would find that a circle of radius  $r$  has a circumference of exactly  $2\pi r$ . But if their world were subtly bent into a saddle shape, it would have a slight negative curvature [see "Inflation in a Low-Density Universe," by Martin A. Bucher and David N. Spergel, on page 62]. The two-dimensional residents of Saddleland might be oblivious to this curvature until they measured a large circle of some set radius and discovered that its circumference was greater than  $2\pi r$ .

Most cosmologists have assumed, for various theoretical reasons, that our three-dimensional space, like Flatland, is not curved. But if it had negative curvature, the large sphere of radiation given off by an ancient supernova would have a greater area than it does in geometrically flat space, making the source appear strangely faint.

A second explanation for the unexpected dimness of distant supernovae is that they are farther away than their redshifts suggest. Viewed another way, supernovae located at these enormous distances seem to have less redshift than anticipated. To account for the smaller redshift, cosmologists postulate that the universe must have expanded more slowly in the past than they had expected, giving less of an overall stretch to the universe and to the light traveling within it.

#### The Force

What is the significance of the cosmic expansion slowing less quickly than previously thought? If the universe is made of normal matter, gravity must steadily slow the expansion. Little slowing, as indicated by the supernovae measure-



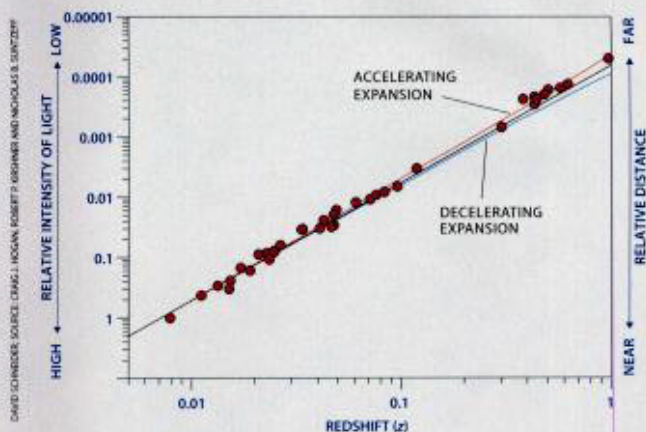
ments, thus implies that the overall density of matter in the universe is low.

Although this conclusion undermines theoretical preconceptions, it agrees with several other lines of evidence. For example, astronomers have noted that certain stars appear to be older than the accepted age of the universe—a clear impossibility. But if the cosmos expanded more slowly in the past, as the supernovae now indicate, the age of the universe must be revised upward, which may resolve the conundrum. The new results also accord with other recent attempts to ascertain the total amount of matter, such as studies of galaxy clusters [see “The Evolution of Galaxy Clusters,” by J. Patrick Henry, Ulrich G. Briel and Hans Böhringer; *SCIENTIFIC AMERICAN*, December 1998].

What does the new understanding of the density of matter in the universe say about its curvature? According to the principles of general relativity, curvature and deceleration are connected. To paraphrase John A. Wheeler, formerly at Princeton University: matter tells space-time how to curve, and space-time tells matter how to move. A small density of matter implies negative curvature as well as little slowing. If the universe is nearly empty, these two dimming effects are both near their theoretical maximum.

The big surprise is that the supernovae we see are fainter than predicted even for a nearly empty universe (which has maximum negative curvature). Taken at face value, our observations appear to require that expansion is actually accelerating with time. A universe composed only of normal matter cannot grow in this fashion, because its gravity is always attractive. Yet according to Einstein's theory, the expansion can speed up if an exotic form of energy fills empty space everywhere. This strange “vacuum energy” is embodied in Einstein's equations as the so-called cosmological constant. Unlike ordinary forms of mass and energy, the vacuum energy adds gravity that is repulsive and can drive the universe apart at ever increasing speeds [see “Cosmological Antigravity,” by Lawrence M. Krauss, on page 52]. Once we admit this extraordinary possibility, we can explain our observations perfectly, even assuming the flat geometry beloved of theorists.

Evidence for a strange form of energy imparting a repulsive gravitational force is the most interesting result we could have hoped for, yet it is so astonishing that we and others remain suitably skeptical. Fortunately, advances in the technology available to astronomers, such as new infrared detectors and the Next Generation Space Telescope, will soon permit us to test our conclusions by offering greater precision and reliability. These marvelous instruments will also allow us to perceive even fainter beacons that flared still longer ago in galaxies that are much, much farther away.



**SUPERNOVA OBSERVATIONS** by the authors' team (red dots) deviate slightly but significantly from the pattern that many theoreticians expected—namely, a fairly rapid deceleration (blue line) that should occur if the universe is “flat” and has no cosmological constant. These observations indicate that the universe has only 20 percent of the matter necessary to make it flat, because it is decelerating more slowly than predicted (black line). The measurements even suggest that expansion is accelerating, perhaps because of a nonzero cosmological constant (red line).

#### The Authors

CRAIG J. HOGAN, ROBERT P. KIRSHNER and NICHOLAS B. SUNTZEFF share a long-standing interest in big things that go bang. Hogan earned his doctorate at the University of Cambridge and is now a professor and chair of the astronomy department at the University of Washington. Kirshner attained his Ph.D. at the California Institute of Technology, studying a type Ia supernova observed in 1972 (the brightest one seen since 1937). He is a professor of astronomy at Harvard University and also serves as an associate director of the Harvard-Smithsonian Center for Astrophysics. Suntzeff received his Ph.D. at the University of California, Santa Cruz. He works at Cerro Tololo Inter-American Observatory in La Serena, Chile, and is made of elements formed in supernovae over five billion years ago.

#### Further Reading

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OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT. Adam G. Riess, Alexei V. Filippenko, Peter Challinor, Alejandro Clocchiatti, Alan Diercks, Peter M. Garnavich, Ron L. Gilliland, Craig J. Hogan, Saurabh Jha, Robert P. Kirshner, B. Leibundgut, M. M. Phillips, David Reiss, Brian P. Schmidt, Robert A. Schommer, R. Chris Smith, J. Spyromilio, Christopher Stubbs, Nicholas B. Suntzeff and John Tonry in *Astronomical Journal*, Vol. 116, No. 3, pages 1009–1038; September 1998. Preprint at [xxx.lanl.gov/abs/astro-ph/9805201](http://xxx.lanl.gov/abs/astro-ph/9805201) on the World Wide Web. Additional information on supernova searches is available at [cfa-www.harvard.edu/cfa/our/Research/supernova/highZ.html](http://cfa-www.harvard.edu/cfa/our/Research/supernova/highZ.html) and [www.supernova.lbl.gov/](http://www.supernova.lbl.gov/) on the World Wide Web.